When a Muon Is Not a Muon— Detecting Fast Long-Lived Charged Particles from Cascade Decays Using a Mass Scan

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Abstract

If produced at the LHC, long-lived charged particles (LLCPs) would leave tracks in the muon detector. Time-of-Flight based methods for detecting these particles become less efficient if the LLCPs are fast, which would typically be the case if they are produced in the decays of some mother particle which is either heavy or very boosted. Thus for example, in supersymmetric models with long-lived sleptons, the long-lived sleptons produced in neutralino decays are often fast, with $\beta \geq 0.95$ even at a 7 TeV LHC. We propose to use the (mis-measured) invariant mass distribution of "muon"-lepton pairs, where the "muon" could be a slepton LLCP, to detect it. This distribution peaks somewhat below the neutralino mass. The peak can be further enhanced by evaluating the distribution for different values of candidate "muon" masses. We simulate two GMSB-like models to show that this procedure can be used to detect the long-lived sleptons and measure both their mass and the neutralino mass.

I. INTRODUCTION

Throughout the past four decades, collider experiments have unveiled the full structure of the Standard Model (SM), by gradually discovering a series of new, unstable particles through their decays to known light particles. It is perfectly plausible however that new particles beyond the SM are stable on collider-detector time-scales, by virtue of some new symmetry that forbids or suppresses their decays. If such new particles are charged, they must decay on cosmological time-scales, potentially leading to rich and testable dark matter scenarios [1]. Indeed, many extensions of the SM predict Long-Lived Charged Particles (LLCPs) that would not decay in the LHC detectors. These include for example sleptons in gauge-mediated or gravity-mediated supersymmetry-breaking models with a light gravitino, or KK-leptons in extra-dimension models (see for example the review [2] and references therein).

If produced at the LHC, an LLCP would traverse the entire detector, much like a muon, but unlike a muon, its speed β would be smaller than one. There has been significant progress in recent years on (i) modifying trigger algorithms to ensure that LLCPs are not missed altogether if they are very slow, (ii) developing techniques for LLCP detection [3–8]. The latter, which have already led to the exclusion of various LLCP models [6–8], mostly rely on the low LLCP speed in order to distinguish it from a muon. At the LHC, LLCPs could be produced either directly, or in cascade decays of heavier particles[1]. A large fraction of the latter may have β close to one[2]. These fast sleptons will be hard to distinguish from muons based on Time-of-Flight methods. Fortunately, the fact that such fast LLCPs typically originate from the decay of a heavy particle, can provide new handles on them. Consider a long-lived slepton $\tilde{l}$ which is produced in association with a lepton l from a neutralino decay, $\tilde{\chi}^0 \to \tilde{l}^{\pm} l^{\mp}$. If the slepton is fast, it can be mistaken for a muon, so that its 4-momentum is not measured correctly. The (mis)measured invariant mass of the opposite-sign (OS) lepton-slepton pair is therefore different from the neutralino mass. Still, if the fast slepton originated from a boosted neutralino, its mass is small compared to all the energy scales characterizing the decay, so that the mis-measured invariant mass distribution would peak somewhat below $m_\chi{}^2 - m_{\tilde{l}}{}^2$. This peak may be observable above the background. Furthermore, the peak can be enhanced by scanning over the possible slepton masses in order to obtain the correct neutralino peak. Taking all the OS "muon"-lepton pairs (where the "muon" could be either a real muon or a slepton LLCP), we can assign the "muon" a trial mass m_{SCAN}, and calculate the resulting "muon"-lepton invariant mass. Varying m_{SCAN}, we will find that the highest peak in the "muon"-lepton distribution is obtained when m_{SCAN} coincides with the true slepton mass. If this peak is indeed observable over the background, one can isolate the LLCP candidates. In the process, both the slepton and neutralino masses are measured, the first from the best value of m_{SCAN}, and the second from the position of the invariant mass peak, calculated with the correct slepton mass. Finally, since at the end of the process the slepton and lepton 4-momenta are fully measured, one can hope to obtain information about the slepton and neutralino couplings and spin, as well as reconstruct the full event [9].

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[1] Thus for example, long-lived sleptons could come from Drell-Yan pair production, from cascade decays of strongly interacting particles, or (if the masses of these strongly interacting particles are very large), from the electroweak production of gauginos, followed by the decay of these gauginos to lighter sleptons.

[2] This would be even more of a problem if the LHC eventually goes to 14 TeV.

The applicability of our methods depends of course on the flavor of the LLCP. As a first step, we will study here a GMSB-like example with degenerate, long-lived right-handed sleptons, and consider only "muon"-electron pairs, which have little SM background in comparison with di-muon pairs. On the other hand, compared to models in which a single slepton is meta-stable, our model results in a factor of three reduction in the efficiency for sleptons. Furthermore, uncorrelated stau-electron and smuon-electron pairs contribute to the SUSY combinatorial background. It would be interesting to extend our approach to models with a single LLCP slepton, whether it is a stau, a selectron or a smuon, and we plan to investigate this in more detail in the future.

II. THE SLEPTON-LEPTON MIS-MEASURED INVARIANT MASS DISTRIBUTION

When a high β slepton goes through the muon detectors, it can easily be mistaken for a muon. The slepton 3-momentum is then measured correctly, but the energy is computed from this 3-momentum assuming a zero slepton mass. Consider then such a mis-measured slepton, which originates from the neutralino decay $\tilde{\chi}^0 \to \tilde{l}^\pm l^\mp$. The measured, or rather, mis-measured, $\tilde{l}l$ invariant mass is,

$$\hat{m}_{\tilde{l}l}^2 = (p_l + \hat{p}_{\tilde{l}})^2 \,, \tag{1}$$

where p_l is the lepton 4-momentum and $\hat{p}_{\tilde{l}}$ is the mis-measured slepton 4-momentum, obtained from its true 4-momentum by setting the slepton mass to zero.

If the slepton is very fast, as would be the case if its mass $m_{\tilde{l}}$ is much smaller than the neutralino mass m_χ or the neutralino energy, one would expect the $\hat{m}_{\tilde{l}l}$ distribution to peak somewhat below the neutralino mass. Indeed, to leading order in $1 - \beta^2$, where β is the slepton speed in units of c, $\hat{m}_{\tilde{l}l}$ takes the simple form,

$$\hat{m}_{\tilde{l}l}^2 = \left(m_\chi{}^2 - m_{\tilde{l}}{}^2\right) \left(1 - \frac{m_{\tilde{l}}{}^2}{m_\chi{}^2 + m_{\tilde{l}}{}^2} \frac{1 + \cos\theta}{1 - r\cos\theta}\right) \,, \tag{2}$$

where

$$r \equiv \frac{m_\chi{}^2 - m_{\tilde{l}}{}^2}{m_\chi{}^2 + m_{\tilde{l}}{}^2} \tag{3}$$

and θ is the angle between the slepton and neutralino direction in the neutralino rest-frame. We see from (2), that $\hat{m}_{\tilde{l}l}$ is a non-negative monotonically decreasing function of $\cos\theta$ whose maximum is obtained when the slepton and the neutralino are collinear, at $\hat{m}_{\tilde{l}l}^2 \sim m_\chi{}^2 - m_{\tilde{l}}{}^2$ in the fast slepton approximation. We can also invert this equation to obtain $\cos\theta$ in terms of $\hat{m}_{\tilde{l}l}$, yielding the form of the $\hat{m}_{\tilde{l}l}$ distribution,

$$\frac{d\Gamma}{d\hat{m}_{\tilde{l}l}} \propto \frac{1}{(m_\chi{}^2 - \hat{m}_{\tilde{l}l}^2)^2} \left[1 \pm a \frac{m_\chi{}^2 + m_{\tilde{l}}{}^2}{m_\chi{}^2 - m_{\tilde{l}}{}^2} \left(1 - \frac{2m_\chi{}^2 m_{\tilde{l}}{}^2}{m_\chi{}^2 - m_{\tilde{l}}{}^2} \frac{1}{m_\chi{}^2 - \hat{m}_{\tilde{l}l}^2}\right)\right] \tag{4}$$

where $a \leq 1$, and the sign is determined by the neutralino polarization (if the neutralino were a scalar, one would have $a = 0$). Thus, the rate is a monotonically increasing function of $\hat{m}_{\tilde{l}l}$, and peaks near its maximal value which is roughly $m_\chi{}^2 - m_{\tilde{l}}{}^2$. In the Appendix, we show that this behavior persists beyond leading order in $1 - \beta^2$, but the maximum allowed

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value of $\hat{m}_{\tilde{l}l}$ is in general given by,

$$\hat{m}_{\tilde{l}l}^{2\ \text{max}} = [m_\chi^2 - m_{\tilde{l}}^2] \left[1 - \frac{m_{\tilde{l}}^2}{(E_\chi + |\vec{p}_\chi|)^2} \right] \,, \tag{5}$$

which coincides with $m_\chi{}^2 - m_{\tilde{l}}{}^2$ in the limit of infinite neutralino energy[3].

We can thus try to use the $\hat{m}_{\tilde{l}l}$ distribution to detect the slepton LLCPs. The OS "muon"-lepton invariant mass distribution behaves differently for "muons" which are true muons, and for "muons" which are meta-stable sleptons. The latter have an $\hat{m}_{\tilde{l}l}$ distribution which is monotonically increasing and exhibits a peak at the maximal allowed value of $\hat{m}_{\tilde{l}l}$. In contrast, the invariant mass distribution of real muon-lepton pairs usually falls off for large values of the invariant mass, unless of course the muon-lepton pair is correlated, and comes from the decay of some heavy particle, such as the Z. Such backgrounds are however reducible, and can be eliminated, unless of course $m_\chi{}^2 - m_{\tilde{l}}{}^2$ happens to lie close to the Z mass.

III.   THE $\hat{m}_{\tilde{l}l}$ DISTRIBUTION IN A GMSB-LIKE MODEL AT A 7 TEV LHC

In order to demonstrate our techniques, we simulate two GMSB-like models for a 7 TeV LHC with the SUSY-breaking parameters

$$\Lambda = 5 \times 10^4 \text{ GeV}\,, \text{ M}_{\text{msg}} = 2.5 \times 10^5 \text{ GeV}\,, \text{ N}_5 = 3\,, \tan\beta = 5\,, \text{ sign}\mu = +\,, \text{ C}_{\text{grav}} = 5000\,. \tag{6}$$

Here Λ is the ratio of the GMSB-singlet F term to the messenger scale [10, 11], N_5 is the number of messenger multiplets, and the parameter C_{grav} is the ratio of the gravitino mass to what it would be if the only source of supersymmetry breaking were the GMSB singlet F-term [12]. Since the latter F-term is typically generated from larger F-terms, such large values of C_{grav} are quite plausible, resulting in heavier gravitinos compared to the naive GMSB estimate, and therefore in long lifetimes of the Next-to-Lightest-SuperPartner (NLSP). For this choice of GMSB parameters, the NLSP is a right-handed slepton[4]. We list the superpartner masses in Table I. These masses are calculated using SPICE [13], which is based on SoftSUSY [14] and SUSYHIT [15]. Since we are interested in fast LLCPs, we modify this model by taking the three right-handed sleptons to be degenerate with a mass of either 110 GeV or 130 GeV. We will refer to the two models as the 130 and 110 models, according to the NLSP mass.

We generate a total of 10000 SUSY events, corresponding to an integrated luminosity of 146 fb^{-1} at a 7 TeV LHC. These come from strong-strong, strong-weak, and weak-weak pair production, which at leading order have a cross-section of 68 fb. We do not include Drell-Yan slepton pair production, which has a comparable cross-section, since most of the resulting sleptons do not pass our selection cuts.

The dominant relevant SM background comes from $t\bar{t}$ for which we have generated a

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[3] Note that $\hat{m}_{\tilde{l}l} \geq 0$ follows from the fact that p_l and $\hat{p}_{\tilde{l}}$ are both lightlike. $\hat{m}_{\tilde{l}l} = 0$, however, can be obtained only for sufficiently energetic neutralinos, with $E_\chi - |\vec{p}_\chi| < m_{\tilde{l}}$.

[4] Recall that the gaugino masses grow as N_5, while the scalar masses only as $\sqrt{N_5}$. Already for $N_5 = 3$ the neutralino is heavier than the right handed sleptons.

Particle	Mass [GeV]	Particle	Mass [GeV]
$\tilde{\nu}_1$	319	$\tilde{\chi}_2^+$	480
$\tilde{\nu}_2$	319	$\tilde{\chi}_1^+$	348
$\tilde{\nu}_3$	319	$\tilde{g}$	1123
$\tilde{\chi}_4^0$	480	$\tilde{l}_{1,2,3}$	130/110
$\tilde{\chi}_3^0$	424	$\tilde{l}_4$	326
$\tilde{\chi}_2^0$	349	$\tilde{l}_5$	328
$\tilde{\chi}_1^0$	198	$\tilde{l}_6$	328
$\tilde{u}^1$	965	$\tilde{d}^1$	1049
$\tilde{u}^2$	1053	$\tilde{d}^2$	1051
$\tilde{u}^3$	1053	$\tilde{d}^3$	1051
$\tilde{u}^4$	1068	$\tilde{d}^4$	1054
$\tilde{u}^5$	1093	$\tilde{d}^5$	1096
$\tilde{u}^6$	1093	$\tilde{d}^6$	1096
h^0	106	H^0	543
A^0	540	H^+	546

TABLE I: Spectrum of the GMSB model calculated from SPICE. The three lightest slepton masses are set by hand to 130 or 110 GeV.

sample of 420000 events corresponding to a luminosity of 5 fb^{-1} at a 7 TeV LHC. The $t\bar{t}$ sample is produced at leading order with a cross-section of 85 pb. Unless stated otherwise, all the results we show below are normalized to 5 fb^{-1}. To generate events we used MadGraph-MadEvent (MGME) [16], with FeynRules [17]. The resulting events are decayed using BRIDGE [18] and put back into MGME's Pythia-PGS package [19–21] which includes hadronization and initial and final state radiation. The slepton and lepton momenta are then smeared according to reported experimental resolution[5].

In Fig. 1 we show the β-distributions of the sleptons in both models, taken from truth (*i.e.*, before any smearing). Indeed, most of the sleptons are fast. For both models, roughly 50% of the sleptons have $\beta > 0.9$ and 25% have $\beta > 0.95$. As explained in the Introduction, we are interested in fast selectrons which are mistaken for muons. We propose to detect these selectrons through the selectron-lepton mis-measured invariant-mass $\hat{m}_{\tilde{l}l}$. The $\hat{m}_{\tilde{l}l}$ distribution of signal events (*i.e.*, OS $\tilde{e}e$ pairs coming from the decay $\tilde{\chi}^0 \to \tilde{e}^\pm e^\mp$) is shown in Fig. 2 for the two models, with a p_T cut of 20 GeV on both the electron and the selectron. As expected, the distributions increase monotonically and peak near the maximal allowed value of $\hat{m}_{\tilde{l}l}^2 \sim m_\chi{}^2 - m_{\tilde{l}}{}^2$ (see (5)), which is about 150 GeV (165 GeV) for the 130 (110) model.

The relevant backgrounds include uncorrelated OS slepton-electron pairs from SUSY events, with the sleptons in this case being either selectrons, smuons, or staus, and OS

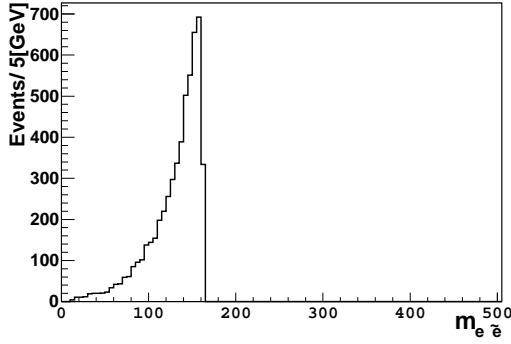
[5] Note that we do not use the PGS detector simulation.
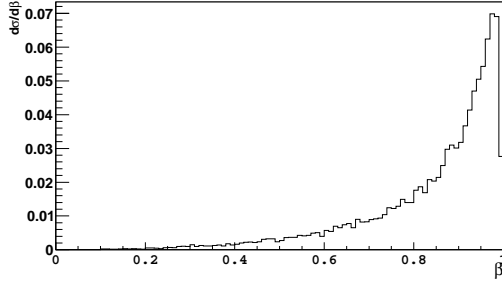
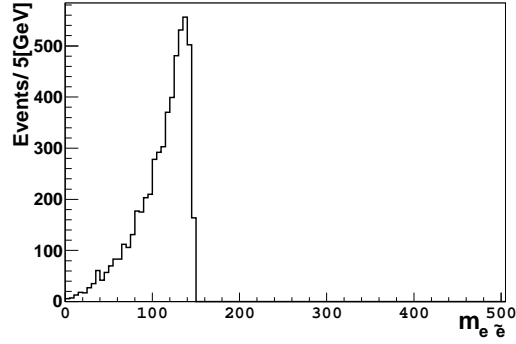(a) Normalized β-spectrum of sleptons for
$m_{\tilde{l}} = 110$ GeV
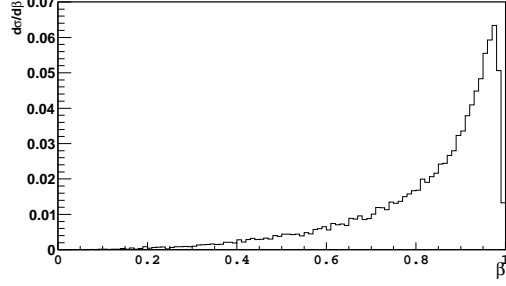
(b) Normalized β-spectrum of sleptons for
$m_{\tilde{l}} = 130$ GeV

FIG. 1: The true beta spectrum (unsmeared momenta) of sleptons.

(a) $m_{\tilde{l}} = 110$ GeV

(b) $m_{\tilde{l}} = 130$ GeV

FIG. 2: The $\hat{m}_{\tilde{e}e}$ distribution of OS $\tilde{e}e$ pairs from the decay $\chi^0 \to \tilde{e}^{\pm}e^{\mp}$, with $p_T > 20$ GeV for both electron and selectron, for 146 fb^{-1}, for the two models.

muon-electron pairs from both SUSY events and SM production. The main source of the latter is $t\bar{t}$ production. To enhance the signal over the background we impose the following cuts:

1. $p_T > 20$ GeV on both "muons" and electrons.

2. $p_T > 100$ GeV and $p > 250$ GeV on the "muon".

3. $\cos\theta_{\tilde{l}l} > 0.6$ where $\theta_{\tilde{l}l}$ is the angle between the "muon" and the electron.

Here and in the following, "muon" denotes either a real muon or a slepton LLCP. The number of events surviving these cuts in each of the models and in the $t\bar{t}$ sample at 5 fb^{-1} are collected in Table II. The combined set of cuts significantly increases the signal-to-background ratio. Still, for the models we study with 5 fb^{-1}, the signal peak is not big enough to dominate the background. In Fig. 3 we show the OS $e\mu$ invariant mass distributions: signal, background (SUSY background and $t\bar{t}$), and signal plus background after the three cuts for the two models, for an integrated luminosity of 5 fb^{-1}. In the signal distribution "muons" are selectrons, whereas in the two other distributions "muons" are either real muons, or any metastable-slepton (selectron, smuon or stau). Although the signal+background distribution

Sample/Cuts	$m_{\tilde{l}} = 110$ GeV			$m_{\tilde{l}} = 130$ GeV		
	Cut 1	Cuts 1+2	Cut 1+2+3	Cut 1	Cuts 1+2	Cut 1+2+3
Signal	189	71	53	189	81	65
SUSY BKG	363	105	30	359	111	33
SUSY Sig+BKG	552	176	83	548	192	98
ttbar	13830	197	70	13830	197	70
Total	14382	373	153	14378	389	168

TABLE II: The number of events surviving the set of cuts described in the text for $m_{\tilde{l}} = 110, 130$ GeV and $t\bar{t}$ normalized to 5 fb^{-1}
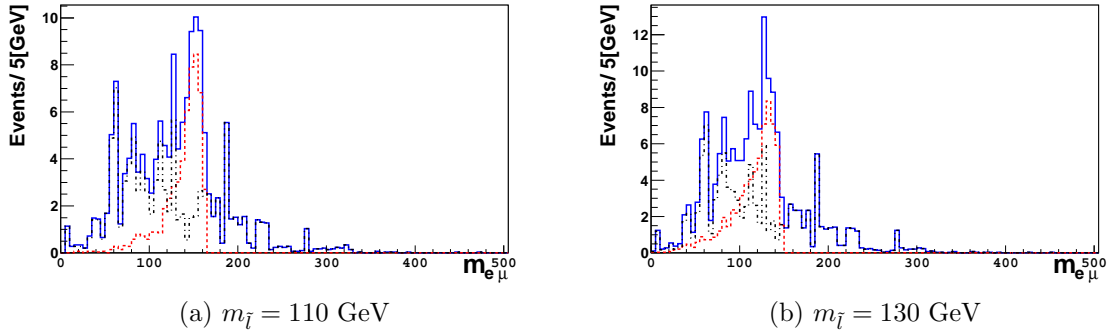

(a) $m_{\tilde{l}} = 110$ GeV

(b) $m_{\tilde{l}} = 130$ GeV

FIG. 3: The invariant mass distributions of OS $e\mu$ pairs after the three cuts in the $m_{\tilde{l}} = 110$ GeV (left) and $m_{\tilde{l}} = 130$ GeV (right) models at 5 fb^{-1}. "Muons" in the signal distribution (red, dash) are selectrons. "Muons" in the background (black, dash-dot) and signal+background (blue,solid) distributions are either muons or any metastable-slepton (selectrons, smuon or stau).

exhibits a small peak near $m_\chi{}^2 - m_{\tilde{l}}{}^2$, it does not clearly indicate the presence of a decaying particle. In the next section, we will see how this peak can be enhanced.

IV.   SCANNING FOR THE SLEPTON MASS

As we saw above, even after our event selection, the signal peak is small compared to the $e\mu$ background coming mainly from $t\bar{t}$ production. It is clear however how to enhance the peak: if we evaluate each "muon" four-momentum with the correct slepton mass, the signal $\hat{m}_{\tilde{l}l}$ distribution would peak at the neutralino mass, while uncorrelated $\mu - e$ pairs would not. As a result, the signal peak may be visible over the background. We therefore study the electron-"muon" invariant mass distributions adding a trial mass m_{SCAN} for each candidate "muon". For each m_{SCAN}, we calculate the maximal bin height, $\zeta_{m_{\mathrm{SCAN}}}$. We expect that the maximal $\zeta_{m_{\mathrm{SCAN}}}$ would occur when m_{SCAN} coincides with the true slepton mass, since then the signal should exhibit the narrowest peak, centered at the neutralino mass. In Fig. 4 we show $\zeta_{m_{\mathrm{SCAN}}}$ as a function of m_{SCAN}, varying the latter over 300 values in the range 100-400 GeV, for the dataset obtained for the 110 and 130 models. Denoting the value of m_{SCAN} at which $\zeta_{m_{\mathrm{SCAN}}}$ is maximal by m_{SCAN}^*, we find that in each of the two

(a) $m_{\tilde{l}} = 110$ GeV　　　　　　(b) $m_{\tilde{l}} = 130$ GeV
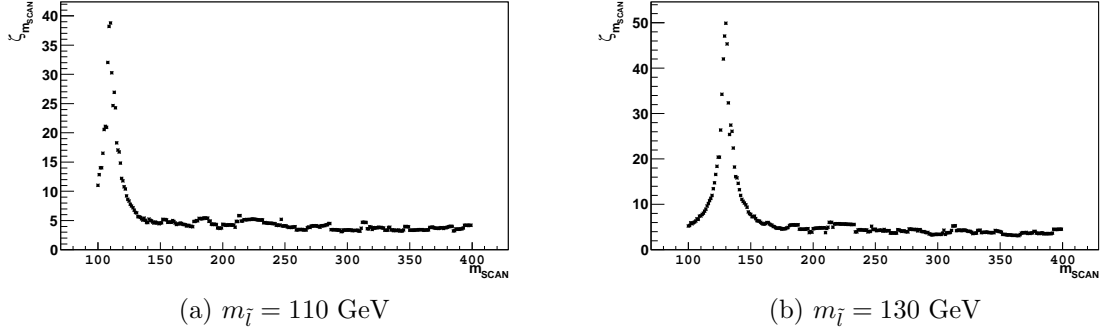
FIG. 4: The ζ measures for each sample mass m_{SCAN}, for the two models.

models, m_{SCAN}^* precisely reproduces the true slepton mass: $m_{\mathrm{SCAN}}^* = m_{\tilde{e}}$. We can now use m_{SCAN}^* to plot the "muon"-electron invariant mass distribution, calculated with m_{SCAN}^* for each "muon" candidate. The results are shown in Fig. 5. The signal peak is clearly visible
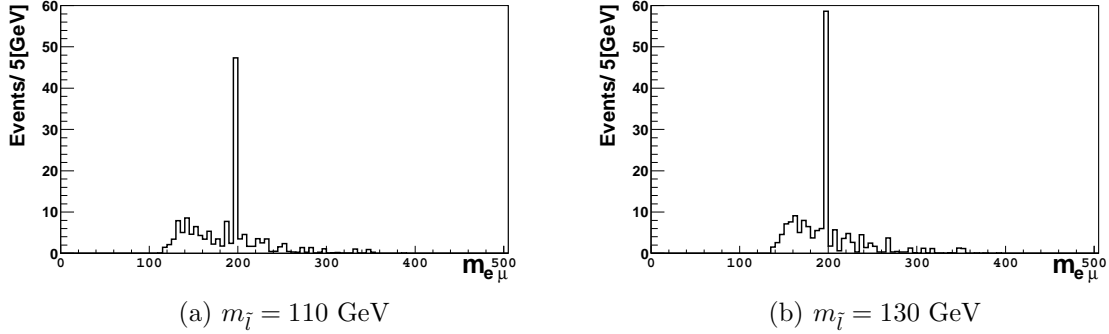

(a) $m_{\tilde{l}} = 110$ GeV　　　　　　(b) $m_{\tilde{l}} = 130$ GeV

FIG. 5: OS "$\mu''-e$ Invariant mass distribution constructed with the mass m_{SCAN}^* for each candidate "muon". Events include both signal and background after cuts.

now over the background.

There are a few things we can learn from these plots. First, the existence of a massive LLCP can be established, and its mass measured to be m_{SCAN}^*. Second, one can now isolate a signal-rich data sample, which includes "muon"-electron pairs whose m_{SCAN}^*-corrected invariant mass lies close to the peak. Each "muon" in this sample can be re-examined, to see whether its track can be distinguished from a true muon. Third, we learn that the LLCPs in the signal originate from the decay of a heavier particle. The mass of this particle is given by the location of the peak in Fig. 5. Finally, with this information, the signal events can be fully reconstructed, allowing for measurements of the masses and couplings of heavier particles with selectron and neutralino daughters.

One could worry that by evaluating the distributions with some arbitrary value of m_{SCAN}, combined with the cuts we use, we are artificially introducing some features into the distributions. Thus for example, for uncorrelated OS muon pairs, with a cut of p_2^{cut} (p_1^{cut}) on the momentum of the slower (faster) muon, one would expect the majority of the leptons to have momenta close to the cut so that the peak of the m_{SCAN}-corrected distribution is obtained for

$$m_{12}^{2,m_{\mathrm{SCAN}}} - m_{12}^2 \sim m_{\mathrm{SCAN}}^2 \left(1 + p_2^{\mathrm{cut}}/p_1^{\mathrm{cut}}\right) , \tag{7}$$

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where m_{12}^2 is the true invariant mass, and $m_{12}^{2,m_{\text{SCAN}}}$ is the m_{SCAN}-corrected invariant mass, evaluated with a mass m_{SCAN} for the faster muon.

To address this issue, we take two different approaches. First, we examine the behavior of the distributions for both wrong values of m_{SCAN} and for $m_{\text{SCAN}} = m_{\text{SCAN}}^*$. This is done in Figs. 6 and 7 where we plot the distributions for 16 values of m_{SCAN} for each model. The
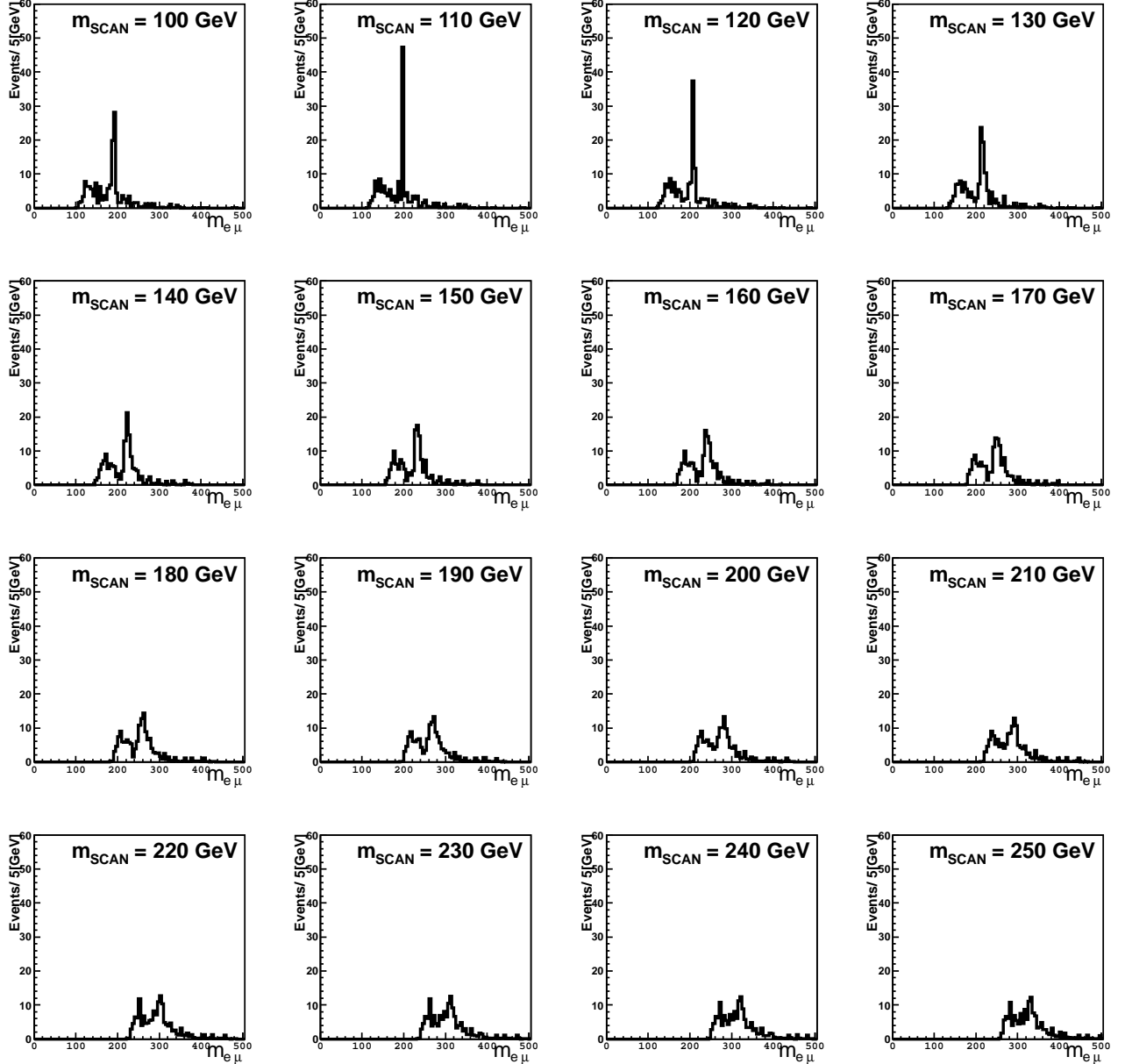

FIG. 6: Invariant mass distributions for each sample mass with $m_{\tilde{l}} = 110$ GeV

results suggest a two-bump structure, with the lower bump presumably corresponding to the background and lying somewhat above m_{SCAN}, consistent with (7). However, for values of m_{SCAN} that are very different from the true slepton mass no distinct features are observed.

Second, we examine the "raw" and m_{SCAN}^*-corrected distributions of the SUSY back-
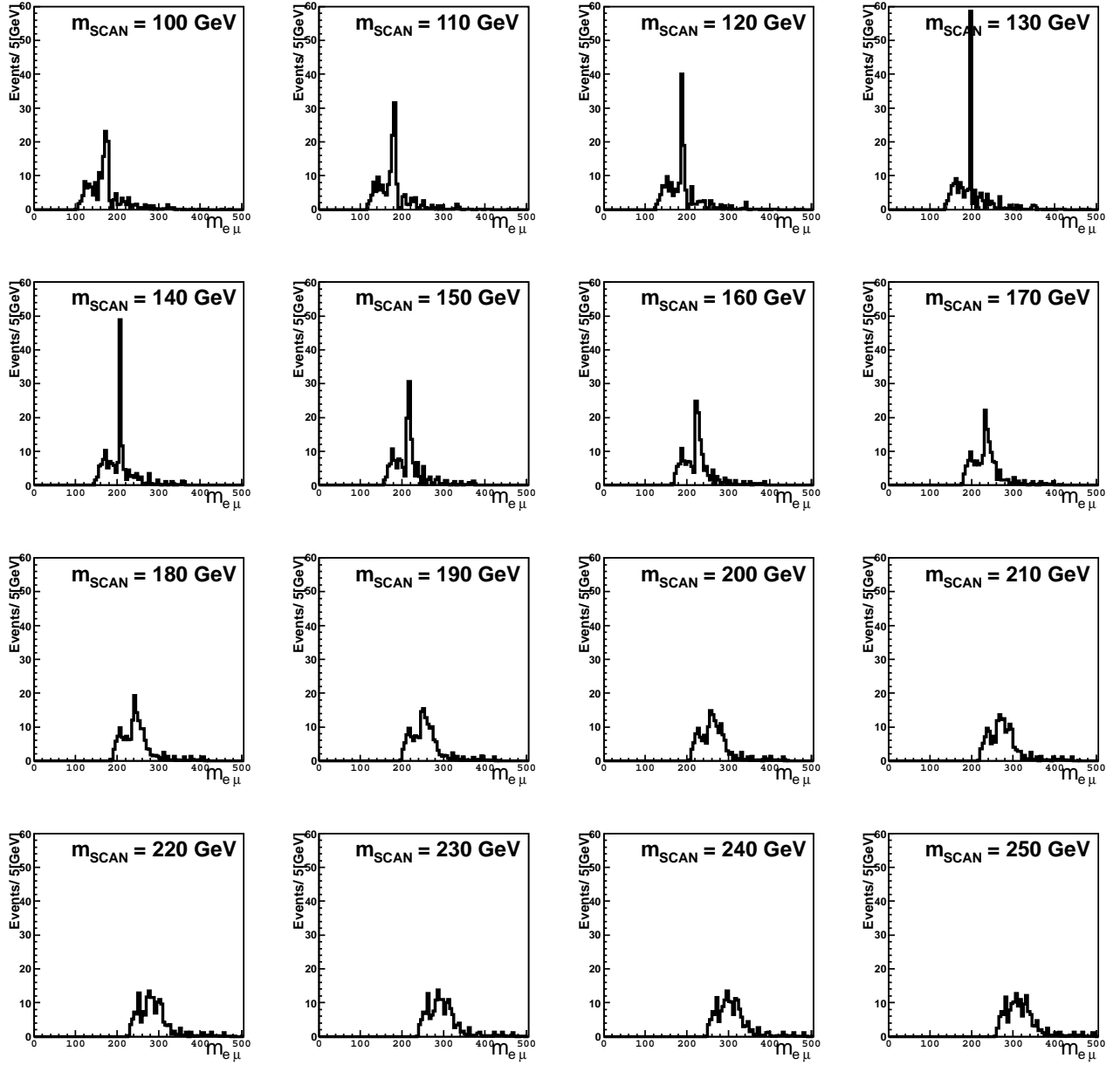
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FIG. 7: Invariant mass distributions for each sample mass with $m_{\tilde{l}} = 130$ GeV

ground and of the $t\bar{t}$ background separately from the signal (see Fig. 8)[6] . Indeed, it is easy to see that including m^*_{SCAN} does not generate any new features in the distributions. In fact, the one feature that does appear in the SUSY background upon including m^*_{SCAN}, is a peak at around 350 GeV, which is nothing but the χ^0_2. Due to the low SUSY cross-section, however, this "peak" contains only one event..

Note that the cross-checks of Fig. 6, Fig. 7, Fig. 8 can be done in a real experiment. This is clearly true for the first two, but also for Fig. 8. To that end, one can isolate the

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[6] We only show the results for the 110 model. The results for the 130 model are very similar.

(a) SUSY background with massless "muon" candidates

(b) SUSY background with massive "muon" candidates of mass $m_{\rm SCAN} = 110$ GeV

(c) $t\bar{t}$ with massless muons

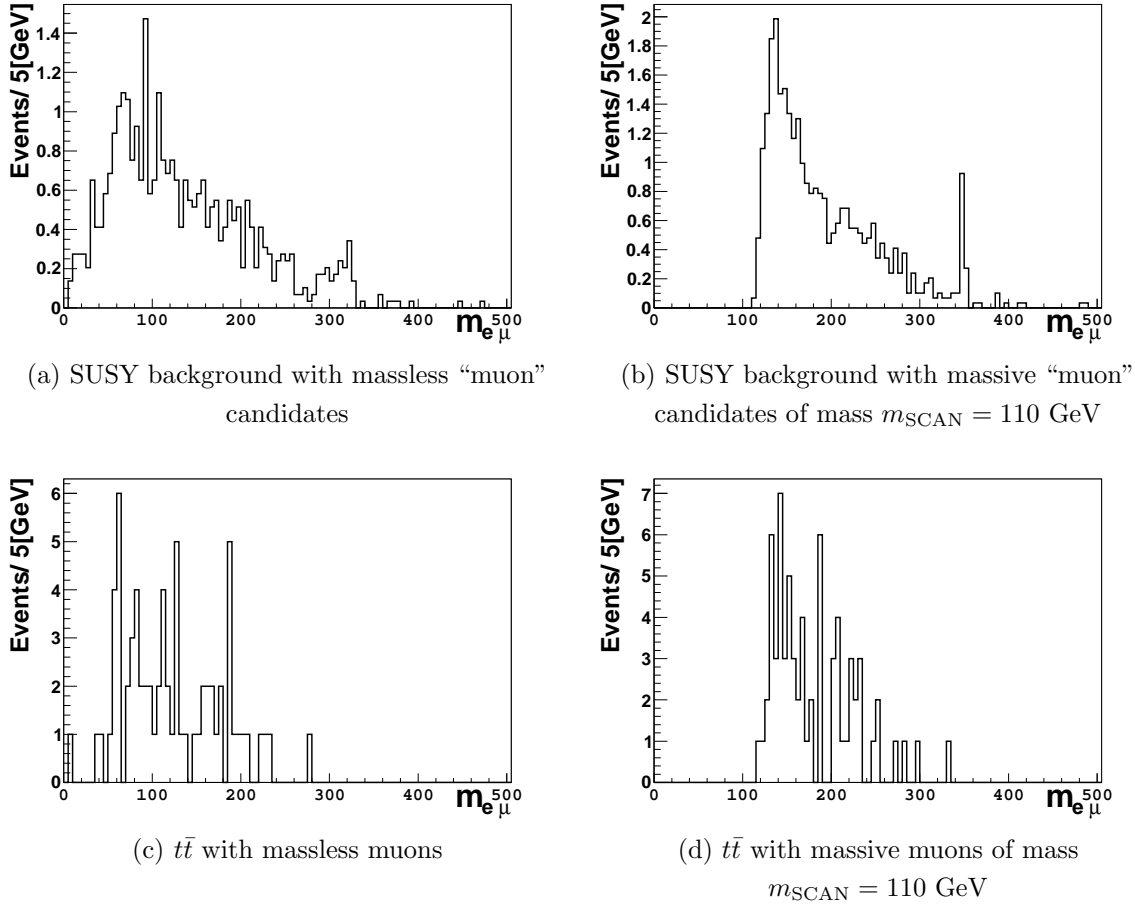(d) $t\bar{t}$ with massive muons of mass $m_{\rm SCAN} = 110$ GeV

FIG. 8: The OS $e\mu$ invariant mass distribution of SUSY background (top) in the 110 model, and of the $t\bar{t}$ background (bottom), after the three cuts. The left panels show the raw distributions, and the right panels show the distributions evaluated with $m_{\rm SCAN} = 110$ GeV. "muons" include both sleptons and real muons in the SUSY background and only real muons in the $t\bar{t}$ background.

signal-rich sample and the background-rich sample as described above, and plot the raw and $m_{\rm SCAN}^{*}$-corrected distribution for each one of them separately.

V. CONCLUSIONS

We have studied a method for detecting fast long-lived sleptons and for measuring their mass. This method relies on the mis-measured invariant-mass distribution of slepton-lepton pairs with the slepton faking a muon. As a first step, we have only studied here a model with three degenerate metastable sleptons. This has both advantages and disadvantages. On the positive side, the model has a metastable selectron, which results in selectron-electron pairs produced in neutralino decays. These produce observable features in the "muon"-electron channel which has very low backgrounds from correlated lepton pairs. On the down side, by using the "muon"-electron channel only, we are keeping only a third of the signal, compared to models with a single metastable slepton. Furthermore, the metastable stau and smuon can also be mistaken for muons, and therefore contribute to the background.

The models in this work were chosen especially for their low cross sections, so that they are not already excluded by time-of-flight or specific ionization methods [6–8]. Though our analysis is only a "leading-order" analysis, it is tempting to estimate the lower limit on the cross-sections of detectable models. From Fig. 5 it is clear that much lower neutralino mass peaks (by approximately a factor of 5) could still be discriminated from the background. The efficiency of the method, however, depends on the neutralino momentum distribution which in turn is affected by the mass spectrum, and is thus model dependent.

The methods we describe would become even more important in a 14 TeV LHC, since then the slepton β-spectrum will peak more sharply near $\beta \sim 1$.

VI.   ACKNOWLEDGEMENTS

Appendix A: Mis-measured Invariant Mass Distribution in a 2-Body Decay

In this Appendix, we will derive the functional form of the $\hat{m}_{\tilde{l}l}$ distribution, and show that it is a monotonically increasing function, and therefore peaks at the maximal value of $\hat{m}_{\tilde{l}l}$. Note that, although the mis-measured slepton momentum $\hat{p}^\mu$ is not a physical momentum, it is nonetheless a 4-vector so that $\hat{m}_{\tilde{l}l}^2$ (see (1)) is Lorentz invariant and the neutralino differential decay rate $d\Gamma/d\hat{m}_{\tilde{l}l}$ can be calculated in any frame. Although it is natural to think of $\hat{m}_{\tilde{l}l}$ in the Lab-frame, since this is where the slepton 3-momentum is measured, it is instructive to express it in terms of the neutralino energy E_χ (in the lab-frame) and the angle θ between the slepton and neutralino direction in the *neutralino rest frame*, since this angle does not depend on the neutralino energy.

We consider the decay $\tilde{\chi}^0 \to \tilde{l}^\pm l^\mp$. In the neutralino rest frame, the particle momenta are:

$$p^\mu|_{\rm rest} = (E_{\tilde{l} \; \rm Rest}, -\vec{p}_{l \; \rm Rest}) \qquad p^\mu_l|_{\rm rest} = (p_{l \; \rm Rest}, \vec{p}_{l \; \rm Rest}) \tag{A1}$$

where p denotes the slepton momentum. and, using energy-momentum conservation,

$$p_{l \; \rm Rest} = \frac{m_\chi^2 - m_{\tilde{l}}^2}{2m_\chi} \qquad E_{\tilde{l} \; \rm Rest} = \frac{m_\chi^2 + m_{\tilde{l}}^2}{2m_\chi} \, . \tag{A2}$$

Taking the neutralino direction to be $+\hat{z}$, and writing the lepton and the mis-measured slepton 4-momenta in the Lab-frame as,

$$p^\mu_{l \; \rm Lab} = (p_l, \vec{p}_{l \; \rm Lab}) \, , \quad \hat{p}^\mu_{\; \rm Lab} = (p, \vec{p}_{\; \rm Lab}) \tag{A3}$$

where

$$p \equiv |\vec{p}_{\rm Lab}| \qquad p_l \equiv |\vec{p}_{l \; \rm Lab}| \, , \tag{A4}$$

we have

$$p_l = \frac{p_{l\ \text{Rest}}}{m_\chi} \left(E_\chi + p_\chi \cos\theta \right) \ . \tag{A5}$$

There are several useful ways to write the mis-measured invariant mass-squared,

$$\hat{m}_{\tilde{l}l}^2 \equiv \left(p_{l\ \text{Lab}}^\mu + \hat{p}^\mu{}_{\text{Lab}} \right)^2 = (p_l + p)^2 - p_\chi^2 = M^2 - m_{\tilde{l}}^2 - 2p_l(E - p) \,, \tag{A6}$$

where E is the slepton energy, $E = \sqrt{p^2 + m_{\tilde{l}}^2}$. Note that $\hat{m}_{\tilde{l}l}^2 = (p_l + p)^2 - p_\chi^2$ is a function of p_χ and $\cos\theta$.

In the neutralino rest frame, we have

$$\frac{d\Gamma}{d\cos\theta} = \frac{m_\chi^2 - m^2}{32\pi m_\chi^3} |M|^2 \,, \tag{A7}$$

with $|M|^2 = A(1 \pm a\cos\theta)$, where a is a positive constant with $a \leq 1$, and the sign depends on the neutralino polarization.

We can write the differential decay rate in terms of $\hat{m}_{\tilde{l}l}$, using Eqs. (A5) and (A6),

$$\frac{d\Gamma}{d\hat{m}_{\tilde{l}l}} = \frac{|M|^2}{32\pi m_\chi\, p_\chi} \frac{\hat{m}_{\tilde{l}l}}{\sqrt{\hat{m}_{\tilde{l}l}^2 + |\vec{p}_\chi|^2}} \left[\frac{m_{\tilde{l}}^2}{(E_\chi - \sqrt{\hat{m}_{\tilde{l}l}^2 + |\vec{p}_\chi|^2})^2} - 1 \right] \,. \tag{A8}$$

To determine the sign of $d^2\Gamma/d\hat{m}_{\tilde{l}l}^2$ it is convenient to start from expression (A7), and use the chain rule to convert derivatives with respect to $\cos\theta$ into derivatives with respect to $\hat{m}_{\tilde{l}l}$. Doing that, we find that $d\Gamma/d\hat{m}_{\tilde{l}l}$ is a monotonic function of $\hat{m}_{\tilde{l}l}$.

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